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A review on electrical and thermal energy for industries

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ABSTRACT

Energy is a vital input for social and economic development of any nation. Currently the industrial sector is consuming about 37% of the world's total delivered energy use for diverse activities in manufacturing, agriculture, mining, and construction. It was reported that global industrial energy consumption is estimated to grow from 5.129E+07 GWh in 2006 to 7.198E+07 GWh in 2030 for the next 25 years. Presently, fossil fuel based energy such as oil, coal, and natural gas are the major sources of energy for industrial activities. Over 80% of total industrial energy needs are met by fossil fuels. Burning fossil fuels produces carbon dioxide which is responsible for negative impacts to the environment. This paper aims at reviewing diverse types of fuels used in industries. It starts with reviewing world fuel consumption trends, world carbon dioxide emissions and fuel consumption trends in industry. Characteristics including fuels energy contents, density, composition, emissions factors and many others factors have also been reviewed. This paper also reflects the possibility of using alternative fuels in industries. It has been found that switching to alternative fuels can offer many social and economic advantages and will result in a positive impact on the environment. Moreover, many alternative fuels have been found to have good energy content those are comparable with fossil fuels.

Contents

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1. Overview of industrial energy consumption in the world

Energy is a vital input for social and economic development of a nation. Global population and energy needs are increasing day by day. It has been found that total world population rose from 6085 million in 2000 to 6849 million in 2010 and projected to reach 9346 million in 2050 as shown in Fig. 1. It is also expected that the average increase in population growth between 2010 and 2020 is projected to be 10.74%. Thus, this issue must be addressed by the international community to overcome any shortage of energy resources in future [1,2].

It is anticipated that the total world energy consumption will be increased by 33.5% from 2010 to 2030. Total world energy use increased from 8.294E+07 GWh in 1980 to 1.166E+08 GWh in 2000 and is expected to reach 1.987E+08 GWh in 2030 as can be seen in Fig. 2 [3].

The most rapid growth in energy demand from 2006 to 2030 is projected for nations outside the Organization for Economic Cooperation and Development (non-OECD nations). This is because, OECD countries are moving from manufacturing to service economies. Total non-OECD energy consumption was increased by 73% compared to a 15% increase in energy use among the OECD countries. The USA consumed about 25% of the world's energy consumption. However, the most significant growth of energy consumption is currently taking place in China. Currently energy consumption in China is at the most significant rate of 5.5% per year [3]. Energies are spent for manufacturing processes and assembly, space conditioning, transportation, and lighting of an industrial facility. Projected energy consumption in OECD, non-OECD countries are presented in Fig. 3 [3–5]. In this projection a 1.7% annual growth is observed.

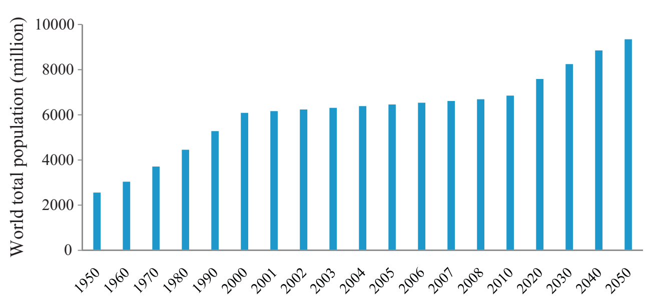

Fig. 1. Total population of the world (million) between 1950 and 2050 [1].

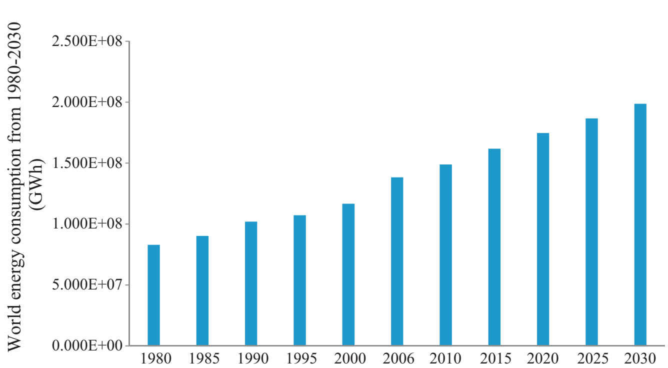

Fig. 2. World energy consumption from 1980 to 2030 (GWh) [3].

2. Global fuel consumption trends

Presently, fossil fuel based energy such as oil, coal, and natural gas are the major sources of energy for industrial activities. Over 80% of total industrial energy needs are met by fossil fuels. Fig. 4 presents fossil, nuclear, and renewable energy use for the year 2005 throughout the world. It may be reported that oil is the largest single source of energy (i.e. 40%) followed by coal, natural gas, nuclear and renewable as can be seen in Fig. 4.

2.1. Oil

It is estimated that about 57 ZJ of proven and recoverable oil is reserved on the earth. World oil production according to US EIA data is expected to grow from 86.1 million barrels per day in

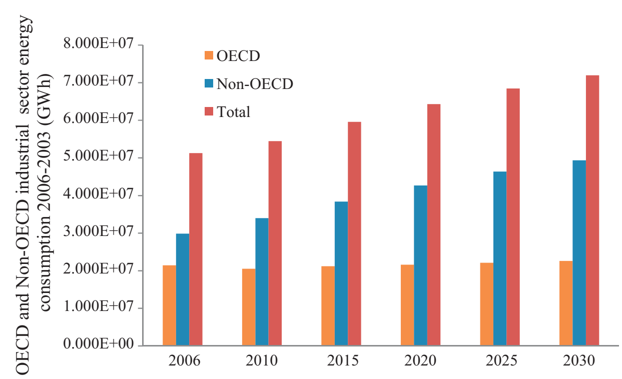

Fig. 3. OECD and non-OECD industrial sector energy consumption from 2006 to 2030 (GWh) [3–5].

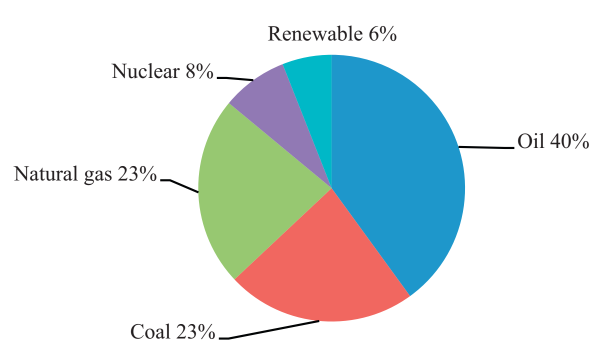

Fig. 4. Statistics of worldwide fossil, nuclear, and renewable fuels consumption in 2005 [6].

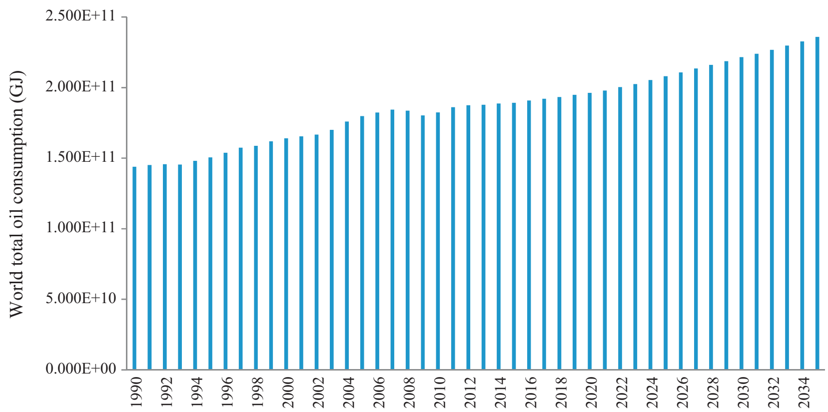

Fig. 5. World oil consumption (GJ) from 1990 to 2035 [3].

2007 to 92.1 million barrels per day in 2020, 103.9 million barrels per day in 2030, 110.6 million barrels per day in 2035. These are used mainly in the industrial and transportation sector for various activities. To meet the increasing demand, oil production needs to be increased by a total of 24.5 million barrels/day from 2007 to 2035. There is a speculation about the peak oil production. A 2005 French Economics, Industry and Finance Ministry report suggested it may occur in 2013. However, few models predicted the peak year to be in 2010, while other models predicted that the peak has already taken place in 2005. There are few studies that reported the peak extraction will be occurred in 2020. World oil consumption is projected to increase from 1.439E+11 GJ in 1990 to 1.641E+11 GJ in 2000 to 1.824E+11 GJ in 2010 and 2.359E+11 GJ in 2035 at an average annual increase of 1.1% as shown in Figs. 5 and 6 shows world oil consumption breakdown in 2004 [3,7].

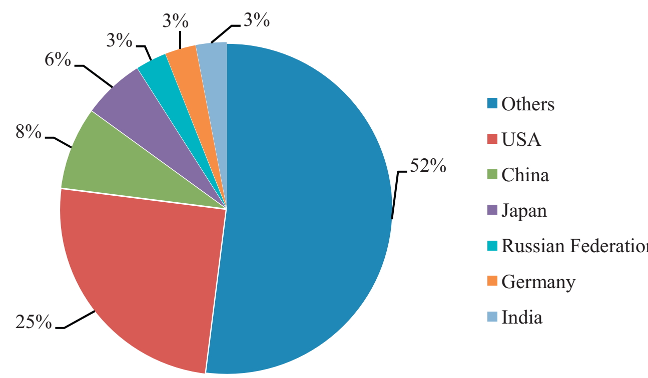

Fig. 6. World oil consumption breakdown in 2004 [7].

2.2. Coal

Globally, coal is the most abundant and cheapest form of fossil fuel. In the United States, about 49% of electricity is generated by burning coal. Moreover, in China the installed coal-fired generating capacity was increased for more than double from 2007 to 2035. Coal use in China's industrial sector has grown by 55%. According to the international energy agency, the proven reserves of coal are around 909 billion tons. This may sustain with the current production rate for about 155 years. Total world coal consumption has increased from 9.411E+10 GJ in 1990 to 9.738E+10 GJ in 2000 to 1.374E+11 GJ in 2010 and to 2.176E+11 GJ in 2035 at an average annual increase of 1.9% as shown in Fig. 7 [3].

2.3. Natural gas

The role of natural gas in the world's energy supply is growing rapidly. Natural gas is the fastest growing primary energy source in the world. World natural gas consumption is expected to increase by 44%, from 108 trillion cubic feet in 2007 to 156 trillion cubic feet in 2035. The industrial sector currently consumes more natural gas than any other end-use sector. It is expected to continue as the major source of energy supply until 2035. It is

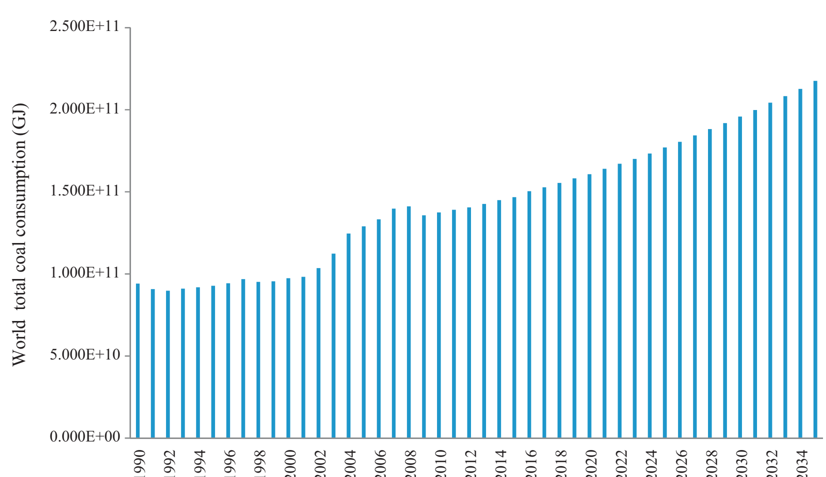

Fig. 7. World coal consumption (GJ) from 1990 to 2035 [3].

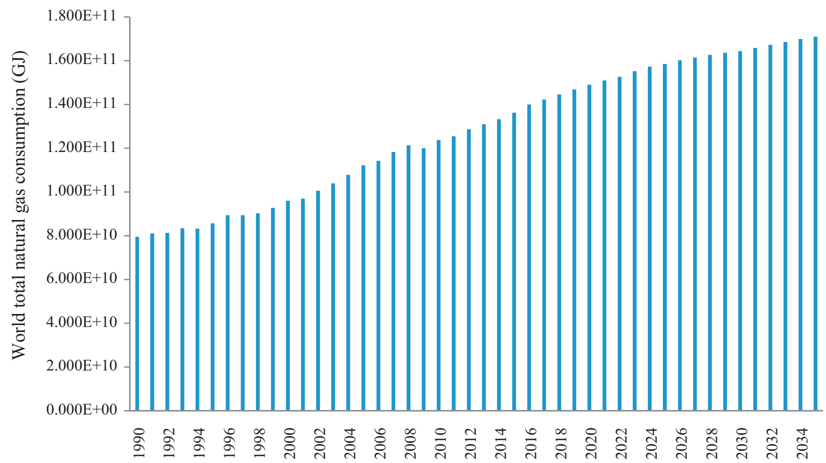

Fig. 8. World natural gas consumption (GJ) from 2000 to 2035 [3].

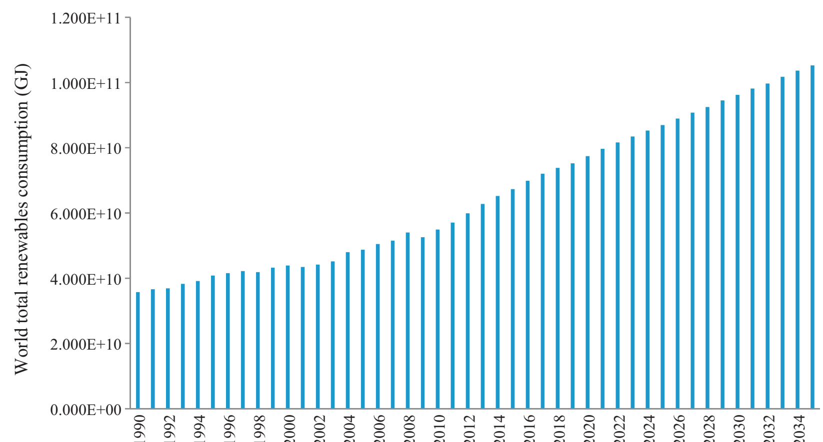

Fig. 9. World renewable consumption (GJ) from 1990 to 2035 [3].

also expected that 39% of the world's natural gas supply will be consumed by that time. World natural gas consumption is projected to increase from 7.955E+10 GJ in 1990 to 9.601E+10 GJ in 2000 to 1.238E+11 GJ in 2010 and 1.710E+11 GJ in 2035. The average annual rate of increase was estimated to be 1.7% as shown in Fig. 8 [3,6].

2.4. Renewable

World renewable sources of energy consumption is projected to increase from 3.577E+10 GJ in 1990 to 4.389E+10 GJ in 2000 to 5.492E+10 GJ in 2010 and to 1.053E+11 GJ in 2035 at an average annual growth of 2.4% as shown in Fig. 9 [3] (http://www.eia.doe.gov/oiaf/ieo/highlights.html).

2.5. Nuclear

World nuclear consumption is projected to increase from 2.152E+10 GJ in 1990 to 2.711E+10 GJ in 2000 to 2.916E+10 GJ in 2010 and 4.967E+10 GJ in 2035. It is also estimated that it will be increased with an average annual growth rate of 1.65% as can be seen in Fig. 10 [3] (http://www.eia.doe.gov/oiaf/ieo/highlights.html).

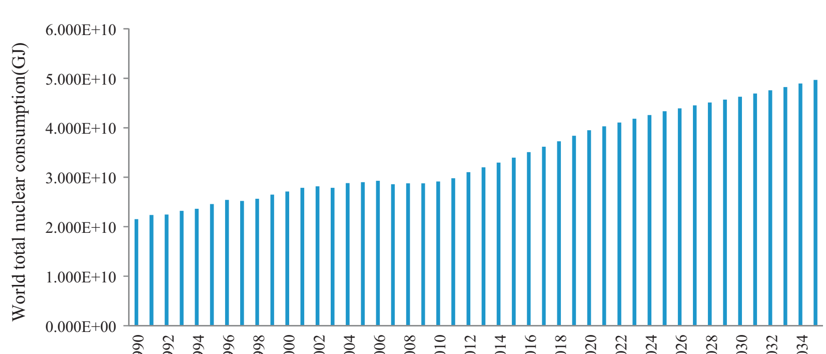

Fig. 10. World nuclear energy consumption (GJ) from 1990 to 2035 [3].

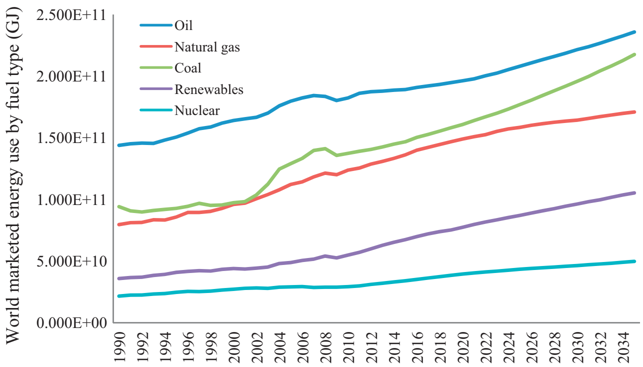

Fig. 11. World marketed energy use (GJ) by fuel type from 1990 to 2035 [3].

Fig. 11 represents a summary of world marketed energy use of petroleum, natural gas, coal, renewable and nuclear from 1990 to 2035. From this figure it can be observed that petroleum is still the dominant source of energy around the world followed by coal and natural gas. Renewable and nuclear come at the end of energy use.

3. World carbon dioxide emissions

It is expected that about 4.1 billion metric tons of carbon dioxide will be released to the atmosphere from 2007 to 2020. It was also estimated that another additional 8.6 billion metric tons carbon dioxide will be released to the atmosphere from 2020 to 2035. This was estimated to about 43% increase for the aforementioned projected period. Fig. 12 shows the emission trends for OECD and non-OECD countries' until 2035 [3].

4. Fuel consumption trends in industry

Normally, fuel prices are important determinants that shape the mix of fuel consumption in the industrial sector of a country. It is a usual tendency for industrial enterprises are to choose the cheapest fuels available in the market. Figs. 13–15, respectively, show the global share of different sources of energy [3].

Figs. 16–22 highlight the distribution of fuels used for few selected countries around the world.

5. Characteristics of conventional fuels used in industries

A comparison of industrial fuels must examine the following characteristics: (1) cost per barrel, ton or BTU as a raw material; (2) availability in any kind of weather and any international political climate; (3) complexity of the on-site equipment need to transport and burn the fuel; (4) problems associated with the storage of the fuel; and (5) emissions caused by the combustion (6) physical, chemical and caloric values of fuels. Table 1 shows an example of current prices for fossil fuels. Table 2 shows emission factors of some fossil fuels. The next section shows some characteristics of conventional fuels used in industry including coal, oil and natural gas.

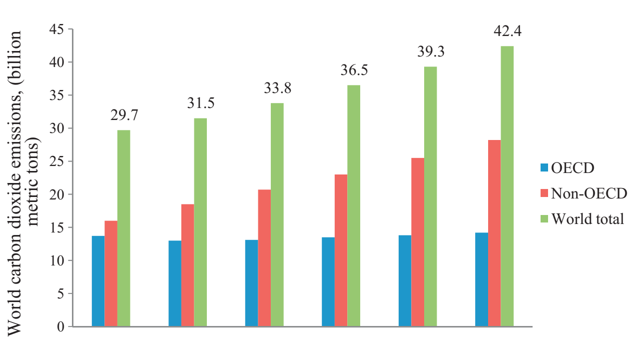

Fig. 12. World carbon dioxide emissions from 2007 to 2035 [3].

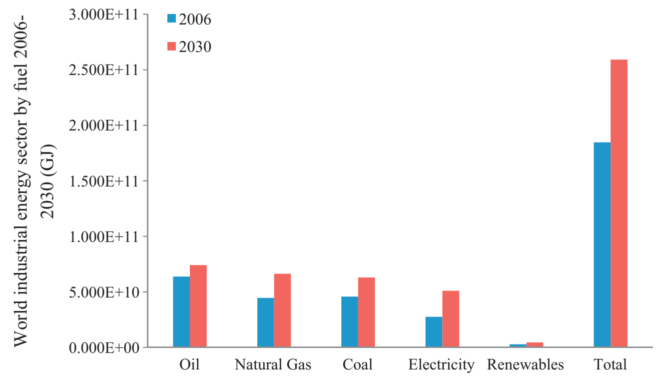

Fig. 13. World industrial energy consumption by fuel in 2006 and 2030 (GJ) [3].

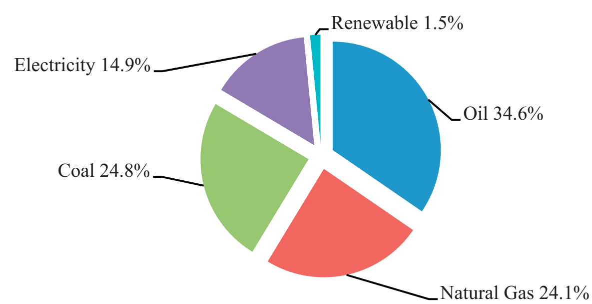

Fig. 14. World industrial energy sector share by fuel in 2006 [3].

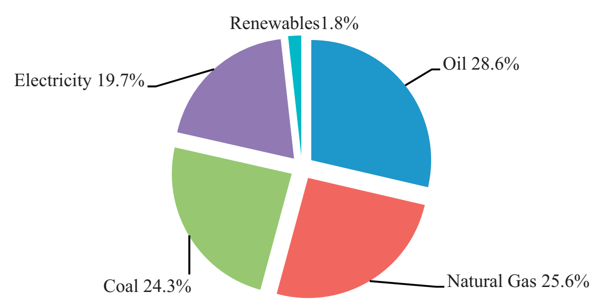

Fig. 15. Projected world industrial energy sector share by fuel in 2030 [3].

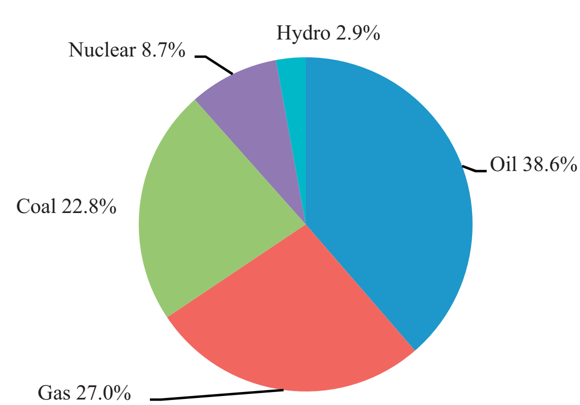

Fig. 16. Total energy consumption in USA by fuel in 2009 [7].

Table 1
History of fossil fuels prices from 2000 to 2008 [7].

Year	Oil			Coal		Natural gas	
	USD dollars per barrel			US dollars per ton		US dollars per million Btu	
	Dubai	Brent	Nigerian Farcados	Northwest Union	US	European Union	US
2000	26.20	28.50	28.32	35.99	29.9	3.25	4.23
2001	22.81	24.44	24.23	39.29	49.74	4.15	4.07
2002	23.74	25.02	25.04	31.65	32.95	3.46	3.33
2003	26.78	28.83	28.66	42.52	38.48	4.40	5.63
2004	33.64	38.27	38.13	71.90	64.33	4.56	5.85
2005	49.35	54.52	55.69	61.07	70.14	5.95	8.79
2006	61.50	65.14	67.07	63.67	62.98	8.69	6.76
2007	69.19	72.39	74.48	86.60	51.12	8.93	6.95
2008	94.34	97.26	101.43	149.78	116.14	12.61	8.85

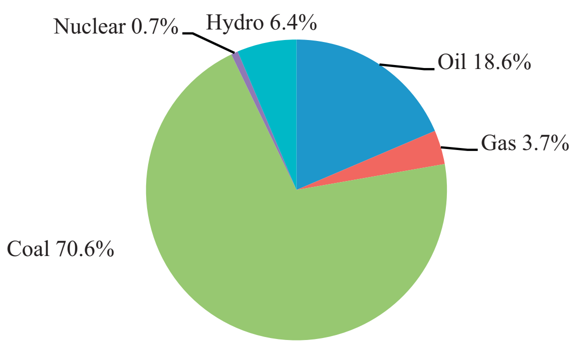

Fig. 17. Total energy consumption in China by fuel in 2009 [7].

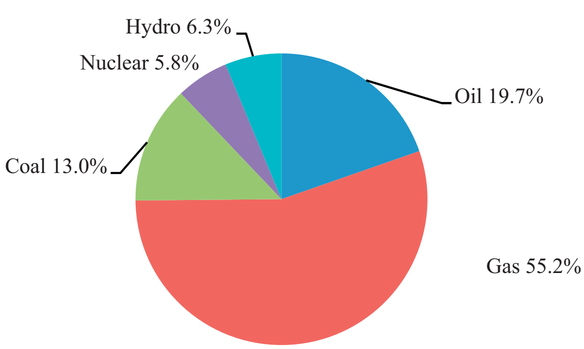

Fig. 18. Total energy consumption in Russian Federation in 2009 [7].

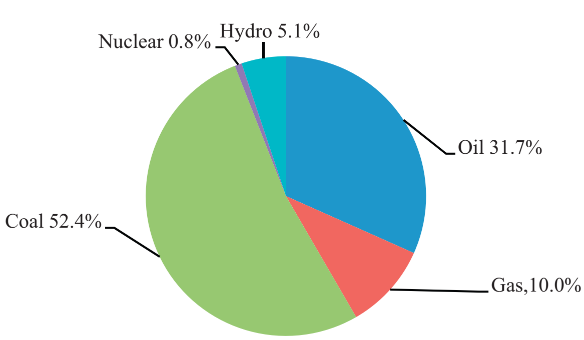

Fig. 19. Total energy consumption in India by fuel in 2009 [7].

Table 2
Emission factors of fossil fuels [9].

Fuels	Emission factor (kg/kWh)			
	CO_2	SO_2	NO_x	CO
Coal	1.18	0.0139	0.0052	0.0002
Petroleum	0.85	0.0164	0.0025	0.0002
Natural gas	0.53	0.0005	0.0009	0.0005

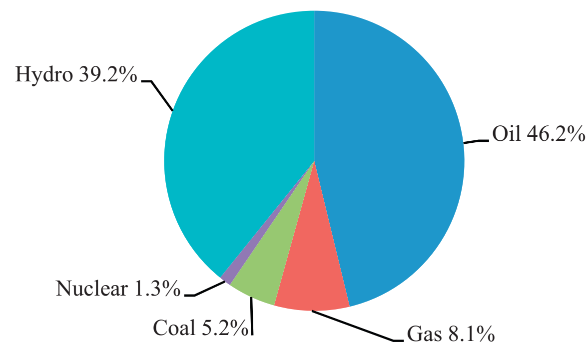

Fig. 20. Total energy consumption in Brazil by fuel in 2009 [7].

5.1. Coal

Coal is the result of the distillation of the original vegetable matter. This transformation is caused by [10]:

(1) Terrestrial heat.
(2) The heat generated in the decomposition of organic matter.
(3) The pressure of the overlying strata.
(4) The convulsions and volcanic eruptions.
(5) The length of time during which the matter has been submerged.

For most industries, coal is the fuel for a choice. This is mainly because coal is an abundant and available fuel. Moreover, it is possible to purchase coal on long-term contracts to keep price fluctuations down. The cost of coal as delivered ranges from $35 to $70 per ton. However, the price is subjected to fluctuate due to weather-caused transportation problems. The technology to burn coal is well-known, and it can be delivered wherever easily. However,

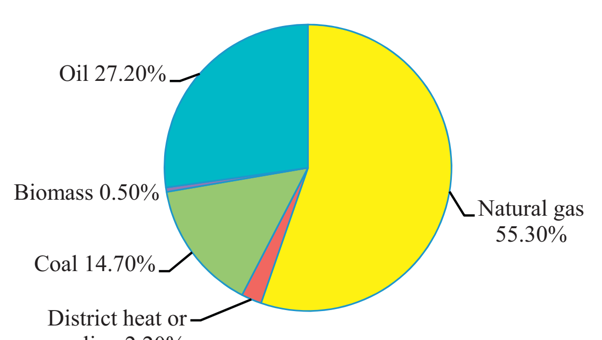

Fig. 21. Distribution of fuels used in the total industrial sector in Malaysia in 2003 [8].

Table 3
Physical, chemical and fuel properties of coal [10,14–16].

Physical properties			
Density (kg/m^3)	1300		
Particle size (μm)	100		
Friability	High		

Chemical composition	Low-rank coal	High-volatility coal	High-rank coal
Carbon (%)	75.2	82.5	90.5
Hydrogen (%)	6.0	5.5	4.5
Oxygen (%)	17.0	9.6	2.6
Nitrogen (%)	1.2	1.7	1.9
Sulfur (%)	0.6	0.7	0.5
Moisture (%)	10.8	7.8	6.5

Heating value (MJ/kg)		
Low-rank coal	High-volatility coal	High-rank coal
31.4	35.0	36.0

Ash composition	
SiO_2content (wet % of dry fuel)	40–60
K_2Ocontent (wet % of dry fuel)	2–6
Al_2O_3 content (wet % of dry fuel)	15–25
Fe_2O_3content (wet % of dry fuel)	8–18

Other properties	
Ash content (%)	12.12
Volatile content (%)	32.50
Inherent moisture (%)	4.38
Ignition temperature (K)	490–595

sulfur oxides and nitrogen oxides emissions as well as particulate matters need to be controlled. The material handling equipment is generally more complex than fuel oil or natural gas. Coal is classified by the amount of specific materials it contains. The classification of coal is made in different ways, the most important of which are according to:

(1) Physical characteristics.
(2) Chemical characteristics.
(3) The calorific value or heat contents.

The behavior of coal is very difficult to predict and quantify. This is mainly due to different coal characteristics from region to region. Coal can be divided into five classes: wood, peat, lignite, coal and anthracite [10,82]. Table 3 shows some physical, chemical properties of coal. There are many other properties that can be found from the literature [11–13].

5.2. Oil

This classification includes from No. 1 such as kerosene to No. 6, a heavy fuel oil. The prices for No. 6 fluctuate around $40 to $85. The availability of this fuel is not affected by weather. The offloading and storage of this fuel is usually uncomplicated, but its viscosity increases in cold weather and may need auxiliary heating before it will flow. Table 4 highlights some properties of diesel. Table 5 highlights energy contents of some petroleum products.

5.3. Natural gas

Compositions of natural gas (NG) are mainly of lightweight alkanes, carbon dioxide, carbon monoxide, hydrogen, nitrogen, and oxygen. In some cases hydrogen sulfide and ammonia are also found. A typical NG may contain methane (CH_4), ethane (C_2H_6), propane (C_3H_8), carbon dioxide, nitrogen, butane and isobutane (C_4H_{10}), and pentanes (C_5H_{12}) [16]. Table 6 shows the compositions of natural gas. Table 7 shows the properties of natural gas [19–22].

Table 4
Fuel properties of diesel [6,17].

Property	Value
Energy content (kJ/kg)	45,000
Density (kg/m^3)	0.85
Flash point	325 K
Kinematic viscosity (at 313 K)	1.3–4.1 mm^2/s
Ash	0.01 max %wt
Sulfur	0.05 max %wt
Cetane number	40

Table 5
Approximate heat content values for petroleum [18].

Fuel	Approximate heat content (MJ/kg)
No. 2 oil (light oil)	46
No. 4 oil (heavy oil)	45
No. 6 oil (heavy oil)	44

Table 6
Compositions of natural gas [19–24].

Item	CH_4	C_2H_6	C_3H_8	N_2	CO_2	Others
Volumetric fraction (%)	96.16	1.096	0.136	0.001	2.54	0.067
	97.30	2.10	0.20	0.30	–	0.1
	92.69	2.95	0.81	2.28	0.89	0.38
	91.2	6.5	1.1	1	–	0.2
	90.35	5.85	2.7	–	–	1.1
	95.24	2	0.7	2.06	–	–

6. Possibility of using alternative fuels in industry

As fossil fuel based sources are limited and expected to be depleted and causing environmental pollution, a sustainable, efficient and cost-effective, convenient, clean and safe sources of energy must be exploited. Globally, there are many approaches and practices that have been developed to conserve energy. Formulation of energy models is one of these approaches that can help in the proper allocation of the available energy sources to meet the current energy demand without affecting the future needs. From the literature it has been found that there are several energy models. Some of the models are related with energy planning, energy supply-demand, forecasting, renewable energy, emission reduction and optimization. Many of these models have been reviewed by several authors [25–30]. Currently, political considerations are also emphasized related to global warming and sustainability to move away from fossil fuels to renewable fuels [31].

Use of renewable resources of energy in an industry may reduce the burden of relying on fossil fuels along with emission reduction [32–35].

Table 7
Properties of natural gas [6,17,19–22].

Property	Natural gas
Energy content (kJ/kg)	55,000
Density at 300 K and 1 atm (kg/m^3)	0.754
Mass lower heating value (MJ/kg)	43.726
Laminar burning velocity (m/s)	0.38
Adiabatic flame temperature in air (K)	2148
Octane number	127
C/H ratio	0.2514
Boiling range (K)	<295

Table 8
Characteristics of fish oil, No. 2 fuel oil and No. 6 fuel oil [38].

Property	Fish oil	No. 2 fuel oil	No. 6 fuel oil
Density at 15 °C (kg/m^3)	880.1	846.5	990.7
Calorific value (MJ/kg)	40.07	45.49	42.74
Flash point, completed closed cup (°C)	178.5	61.0	105.8
Pour point (°C)	4	−46.0	−64
Carbon (wt%)	77.47	86.26	87.5
Hydrogen (wt%)	11.91	12.86	10.32
Sulfur (wt%)	<15 ppm	0.21	1.49
Nitrogen (wt%)	0.001	0.009	0.56
Ash (wt%)	<0.001	<0.001	0.031
Kinematic viscosity cSt at 25 °C	5.76	3.238	5689.7
Kinematic viscosity cSt at 40 °C	4.36	2.484	602.24

There are many countries taking actions as a result of the Kyoto Protocol. A binding target of increasing the level of renewable energy in the EU's overall mix from less than 7% today to 20% by 2020 has been proposed in a recent European Union policy. The European commission, the parliament and the council have recently published three reviews of the community strategy for waste management originally established in 1989. All three documents have a certain flexibility regarding the application of alternative fuels in an industry. This policy is supported by the general principles of waste management at both European Union and national levels [36].

Use of alternative fuels in industrialized countries experienced 20 years of success. The Netherlands and Switzerland are world leaders in the use of alternative fuels. In the US, about 20–70% of their energy needs for cement industries are derived from alternative sources of energy [35].

Maglaya [37] reported that Philippine is utilizing Calatrava coal–diesel oil mixture (CDOM) as an alternative fuel for industrial steam generator. Because this can reduces pollutants like as sulfur and ash. Moreover, the results showed that the CDOM fuel can be used with no degradation of the industrial steam generator. It was also found that the steam generator efficiency using diesel oil is almost similar to the steam generator efficiency using both CDOM fuels.

Fish oil is also another renewable energy source that can be used in industries. A recent study has shown that fish oil can be used as a fuel for diesel engines. Some studies have also examined the combustion characteristics of fish oil and compared it with No. 6 fuel oil and No. 2 fuel oil, respectively. They found them potential fuels for burning in conventional furnace/boilers. Some of these characteristics are tabulated in Table 8. It was reported that blends of fish oil and fuel oils burn easily in the furnace and the boilers up to 100% fish oil content. Emission levels of gaseous pollutants and particulate matter (PM) were compared with those of burning the pure fuel oils and found that the lower level of emission than the pure fuel oil. However, the NO emission was reported to be higher when burning the 10% fish oil blend with No. 6 fuel oil [38–41].

In Germany alternative fuels are used as major sources of energy in cement industries. Fig. 22 shows the usage of alternative fuels in cement industry from 1999 to 2005. It can be seen that the pattern of alternative fuels in industry is increasing steadily and can be applied in many other countries around the world [42].

There are different types of alternative fuels which contain flammable fractions of municipal waste and various modifiers in the form of flammable industrial waste such as [43–45]:

1. Landfills gas, pyrolysis gas, biogas, etc.
2. Liquids such as tar, chemical waste distillation residue, oils, solvents, etc.
3. Solids such as tires, wood waste, plastic, sludge, paper waste, etc.

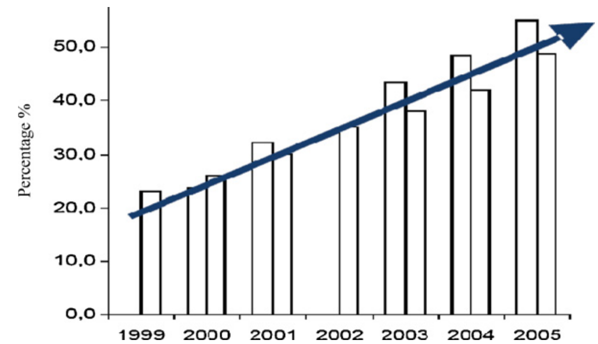

Fig. 22. Usage of alternative fuels in the whole German cement industry from 1999 to 2005 [42].

Other studies show that a list of potential alternative gaseous and liquid fuels for industrial gas turbines can be burned such as [46]:

- Vegetable oils.
- Esters.
- Flash pyrolysis oils.
- Ethanol.
- Methanol.
- Synthetic fuels (biomass to liquids).
- Di-methyl-ether.
- Biogas of gasification.
- Biogas of waste methanisation.
- Biogas of slow pyrolysis.
- Industrial process gases rich in hydrogen.

Mokrzycki and Uliasz-Bocheňczyk [44] and Kaantee et al. [47] highlight some alternative fuels that can be used particularly in the cement plants. These fuels include liquid, solid and gaseous waste fuels as shown in Table 9.

6.1. *Desirable fuel properties*

There are many properties that should be examined before burning of alternative fuels in any industrial applications. Some of these properties are [44]:

(1) Physical state of the fuel (solid, liquid, gaseous).
(2) Content of circulating elements (Na, K, Cl, S).
(3) Toxicity (organic compounds, heavy metals).
(4) Composition and content of ash.
(5) Content volatiles.
(6) Calorific value.
(7) Physical properties (scrap size, density, homogeneity).
(8) Grinding properties.
(9) Humidity content.

Table 9
Alternative fuel option for the cement industry [44,47].

Types of fuel	Example
Liquid waste fuels	Tar, chemical wastes, distillation residues, waste solvents, used oils, wax suspension, petrochemical waster, asphalt slurry, paint waste, oil sludge
Solid waste fuels	Petroleum coke ("petcoke"), paper waste, rubber residues, pulp sludge, used tires, battery cases, plastic residues, wood waste, domestic refuse, rice chaff, refuse derived fuel, nut shells, oil-bearing soil, sewage sludge
Gaseous waste	Landfull gas, pyrolysis gas

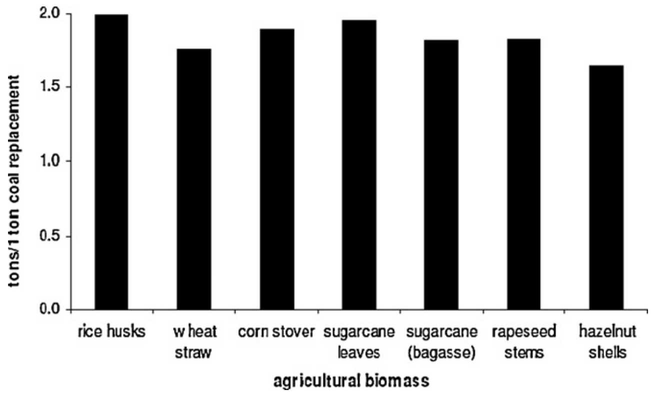

Fig. 23. Tons of agricultural biomass residues necessary to replace 1 ton of coal [35].

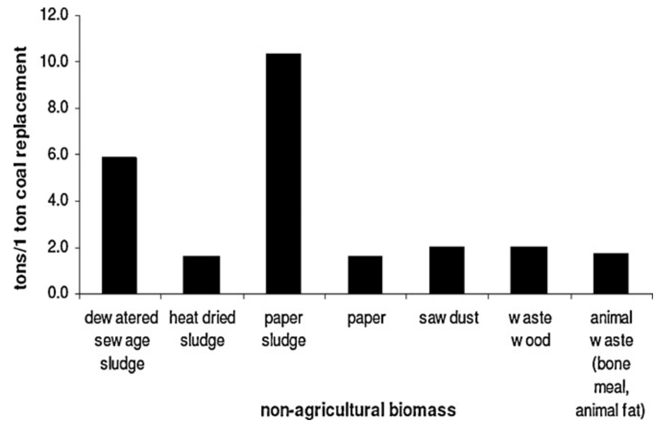

Fig. 24. Tons of non-agricultural biomass residues necessary to replace 1 ton of coal [35].

(10) Proportioning technology.
(11) Combustion characteristics.
(12) Environmental analysis.

6.2. Benefits of using alternative fuels in industry

The use of alternative fuels in industry has numerous benefits such as [45,48–50]:

- Reduction of the use of fossil fuels such as coal as well as the environmental impacts associated with coal mining.
- Contribution towards a lowering of emissions of greenhouse gases by replacing the use of fossil fuels with materials that would otherwise have to be incinerated with corresponding emissions and final residues.
- Maximization of the recovery of energy from waste that would otherwise be disposed of by landfill or incineration.
- Reducing production cost.
- Achieving social sustainability and offering many jobs.
- Economic benefits: biomass could replace some of the money spent on oil.
- Burning of alternative fuels in industry can play a great role in solid waste management strategies of many societies.

6.3. Types of alternative fuels

6.3.1. Agricultural biomass

Agricultural biomass includes rice husks, wheat straw, corn stover, sugarcane leaves, sugar cane bagasse, rapeseed stems, hazelnut shells and palmnut shells. Industrialized countries are using less agricultural biomass fuels compared to developing countries.

The quantity of agricultural biomass residues needed to replace 1 ton of coal is dependent on the energy and water content of the biomass. On an average about 1.6 and 2 ton of biomass residues are needed to replace 1 ton of coal as shown in Fig. 23 [35].

6.3.2. Non-agricultural biomass

Animal byproducts fat, meat and bone meal making are considered as non-agricultural biomass. There are other varieties of non-agricultural biomass such as sewage sludge, paper sludge, waste paper, and sawdust. Recently sewage sludge is being used in industries and is expected to increase its usage in coming years. The quantity of non-agricultural biomass residues that are necessary to replace 1 ton of coal depends on the residue's energy value and water content. A range is 1.6 and 10.3 ton of biomass residues are needed to replace 1 ton of coal. This trend is presented in Fig. 24 [35].

6.3.3. Chemical and hazardous waste

Approved hazardous wastes are also used as alternative fuels in industries with certain extent. These include spent solvent, obsolete pesticides, paint residues, and anode wastes. The quantity of chemical and hazardous wastes that are necessary to replace 1 ton of coal is dependent of the energy and water content of waste fuels. The range is presented in Fig. 25 [35].

6.3.4. Petroleum-based fuels

Waste-based fuels are derived from petroleum products including tires, waste oils, rubber, plastics, petroleum coke (petcoke), and asphalt. Among these fuels, tires and waste oils are the most common. The material's energy and water content are the main determinants to replace coal with waste based fuels. The ranges of replacing petroleum products per ton of coal are shown in Fig. 26 [35].

6.3.5. Miscellaneous fuels

Automobile shredder residue (ASR), carpet residue, textiles, wax residue, landfill gas, and municipal solids waste (MSW) are the fuels those fall under this category. The material's energy and water content are the main determinants to replace coal with these fuels. Fig. 27 shows the quantity of fuel needed to replace 1 ton of coal [35].

6.4. Emissions reduction of using alternative fuels in industry

Alternative fuels are considered as environmentally friendly fuels and have some advantages over fossil fuels such as coal, petroleum and natural gas. Tables 10–12 show many examples that

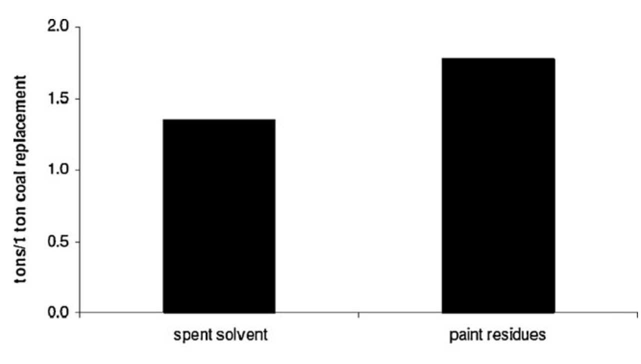

Fig. 25. Tons of chemical and hazardous wastes necessary to replace 1 ton of coal [35].

Table 10
Carbon emissions factor and ΔCO_2 reduction of different alternative fuels [35].

	Alternative fuels	Carbon emissions factor (ton C/ton)	ΔCO_2 (ton/ton Coal replaced)
Agricultural biomass	Rice husks	0.35	−2.5
	Wheat straw	0.42	−2.5
	Corn stover	0.28	−2.5
	Sugarcane leaves	0.34	−2.5
	Sugarcane bagasse	0.39	−2.5
	Rapeseed stems	0.39	−2.5
	Hazelnut shells	0.48	−2.5
	Palmnut shells	0.36	−2.5
Non-agricultural biomass	Dewatered sewage sludge	0.08	−2.5
	Dried sewage sludge	0.24	−2.5
	Paper sludge	0.2	−2.5
	Paper	0.42	−2.5
	Sawdust	0.38	−2.5
	Waste wood	0.34	−2.5
	Animal waste (bone, meal, fat)	0.29	−2.5
Chemical and hazardous wastes	Spent solvent	0.40	−0.95
	Paint residue	0.42	0.06
Petroleum-based wastes	Tires	0.56	−0.8
	Polyethylene	0.70	−1.00
	Polypropylene	0.70	−1.00
	Polystyrene	0.70	−0.90
	Waste oils	0.44	−0.50
	Petroleum coke	0.78	0.2
Miscellaneous wastes	Automobile shredder residue (ASR)	0.44	0.05
	Landfill gas	0.30	−1.0
	Municipal solid waste (MSW)	0.26–0.36	−0.4

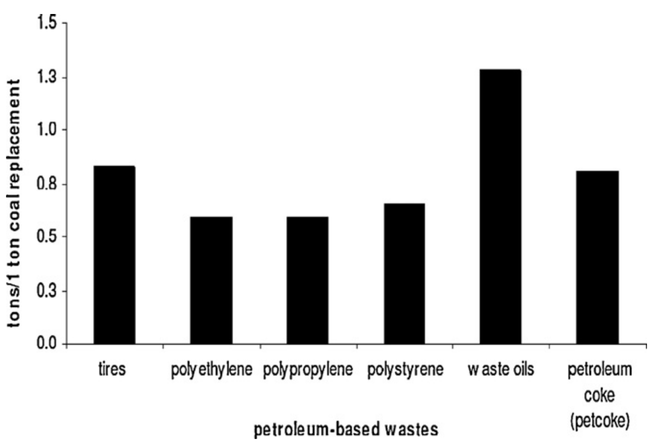

Fig. 26. Tons of petroleum-based wastes necessary to replace 1 ton of coal [35].

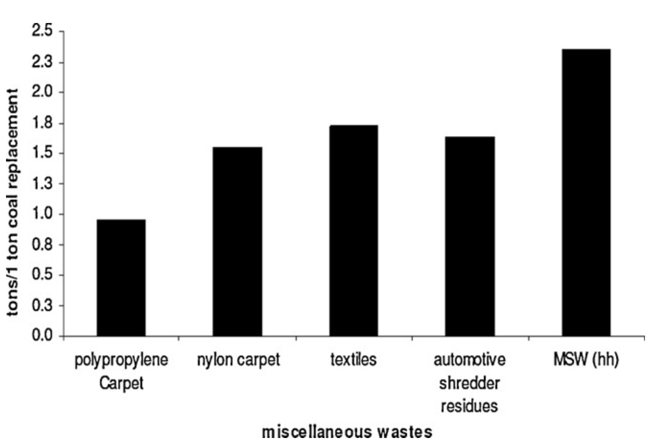

Fig. 27. Tons of miscellaneous wastes necessary to replace 1 ton of coal [35].

Table 11
Emissions factor from switch grass and coal [51].

Emission species	CO_2	N_2O	CH_4	SO_x	CO
Emission factor (g/kg switch grass)	1525	0.09	0.14	0.10	4.12
Emission factors (g/kg coal)	2085	0.031	0.022	17.16	0.25

can demonstrate the emission reduction possibilities of alternative fuels over fossil fuels.

Atabani [53] reported that blending diesel with biomass based palm oil will reduce emissions of CO_2 when used as a boiler fuel. Amount of emission for different percentage of blend for diesel and biomass is shown in Fig. 28.

6.5. *Biomass as a potential substitution to fossil fuels in industry*

Biomass is one of the most available renewable resources of energy contributing to global economy. In the US, cement plants were burning waste oil, scrap tires, solvents, non-recyclable plastics and other materials [16,32,35].

Approximately 985 million tons biomass is produced annually around the world. About 26.23% of primary energy consumption in non-OECD countries is met by using biomass energy. On the other hand, accounts for only 3.4% of primary energy consumption in OECD countries. The breakdown of biomass

Table 12
Emissions factor from electricity generation in the UK [52].

Fuel	Emission factor (g/kWh)		
	CO_2	SO_2	NO_x
Poultry litter	10	2.42	3.90
Forestry residues	24	0.06	0.57
Animal slurry	31	1.12	2.38
Natural gas	446	0.0	0.5
Coal	955	11.80	4.3

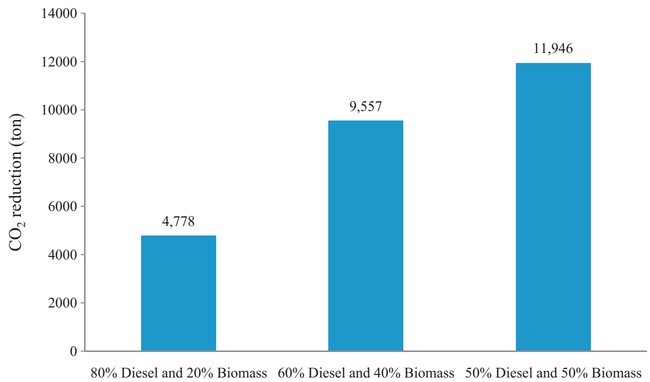

Fig. 28. Total CO_2 reduction (ton) when switching between palm oil biomass and diesel [53].

energy consumption in different world regions is given in Table 13 [2,54,55].

6.5.1. Energy contents of biomass

The heating value, also called calorific value, of the biomass can be defined by the higher heating value (HHV), which is basically the energy content on a dry basis. The lower heating value (LHV) is obtained by deducting the energy needed to evaporate the moisture content of the fuel. Many correlations are available in the literature to calculate higher heating value of biomass. In this paper the correlations are combined into three groups according to the approaches used; estimating the HHV based on the proximate, ultimate and structural analysis. Eleven correlations proposed for estimating the biomass HHV were collected from the literature and shown in Table 14.

As can be seen from Table 14, C and H contents raised the heating value of the fuel. However, oxygen content is responsible for reducing it [61]. Table 15 shows some energy contents of different biomass fuels.

6.5.2. Combustion of biomass

Biomass combustion is a series of chemical reactions where carbon is oxidized to carbon dioxide, and hydrogen is oxidized to water. However, there are many elements that go into the com-

Table 13
The importance and the share of biomass in energy consumption in different world regions in 2000 [2,6,54,55].

Country/region	Share of biomass in final energy consumption (%)
Africa	58.40
Asia	42.30
Bhutan	89
Cambodia	80
China	18.50
Denmark	10.3
Enlarged EU, EU25	3.7
Finland	19.6
Germany	2.1
Laos	80
Latin America	19.57
North America	2.7
Middle east	0.30
Latvia	30.3
Nepal	86
OECD countries	3.4
The old EU countries, EU15	3.7
Total non ECD	26.23
World	14.2

Table 14
HHV correlations and their evaluations.

NO	Correlation (HHV, MJ/kg)	Reference
Based on proximate analysis		
1	$HHV = 0.196(FC) + 14.119$	
2	$HHV = 0.312(FC) + 0.1534(VM)$	
3	$HHV = 0.3543(FC) + 0.1708(VM)$	[56–58]
4	$HHV = 19.914 - 0.2324\ Ash$	
5	$HHV = 14.2 + 0.38(FC) - 9.0721(FC)^2$	
Based on structural analysis		
6	$HHV = 0.0889(L) + 16.8218$	[56,59]
7	$HHV = 0.1739Ce + 0.26631(1 - Ce)$	
Based on ultimate analysis		
8	$HHV = 0.4373C - 1.6701$	
9	$HHV = 0.335(C) + 1.423H - 0.1540$	[16,59,60]
10	$HHV = 0.335C + 1.423(H) - 0.154(O)0.145(N)$	
11	$HHV = (0.3516)(C) + 1.16225(H) - 0.1109(O) + 0.0628(N) + 0.10465(S)$	

Table 15
Typical energy contents of different types of biomass.

Type of biomass	Energy contents (MJ/kg)	Source
Green wood	8	[62]
Oven dry plant matter	20	
Almond shell	19.8	
Almond hulls	20	
Oak wood	19.8	[16]
Switch grass	19.9	
Wheat straw	19.3	
Apricot stones	22.082	
Peach stones	20.657	[63]
Olive cake	19.813	
Tuncbilek lignite	23.212	
Hazelnut seedcoat	19.2	
Olive husk	18.8	
Black locust	19.71	
Tires	36.800	[64]
Municipal solid waste	15.95–17.533	
Poplar	19.38	
Eucalyptus (Grandis)	19.35	
Colza seed	19.38	
Pine cone	18.65	[65]
Cotton refuse	18.83	
Olive refuse	15.77	
Sugar beet	17.40	
Potatoes	17.00	[66]
Rape seed	27.80	
Lucerne	19.0	
Cereals	18.61	
Millet	18.165	[67]
Sunflower	20.262	
Cotton cake	17.50	
Soybean cake	18.30	[58]
Peach bagasse	16.24	
Sourcheery stalk	17.59	
Coir pith	19.50	[68]

Table 16
Combustion properties of biomass samples [14,65].

Sample	Ignition temperature (K)	Maximum combustion rate (mg/min)	Peak temperature (K)
Olive refuse	473	3.40	537
Cotton refuse	423	3.70	598
Pine cone	475	5.20	565
Sunflower	475	5.50	573
Colza seed	423	2.80	535

Table 17
Physical, chemical and fuel properties of biomass and coal fuels.

Property	Biomass	Coal	Reference
Fuel density	500	1300	
Particle size	3 mm	100 μm	
C content (wet % of dry fuel)	43–54	65–85	
O content (wet % of dry fuel)	35–45	2–15	
S content (wet % of dry fuel)	Max 0.5	0.5–7.5	
SiO_2 content (wet % of dry fuel)	23–49	40–60	[14]
K_2O content (wet % of dry fuel)	4–48	2–6	
Al_2O_3 content (wet % of dry fuel)	2.4–9.5	15–25	
Fe_2O_3 content (wet % of dry fuel)	1.5–8.5	8–18	
Ignition temperature	418–426	490–595	
Heating value	14–21	23–28	

bustion. Reaction for the combustion of a biomass fuel in air can be expressed by following equation.

$$C_{x1}H_{x2}O_{x3}N_{x4}S_{x5}Cl_{x6}Si_{x7}K_{x8}Ca_{x9}Mg_{x10}Na_{x11}P_{x12}Fe_{x13}Al_{x14}Ti_{x15}$$
$$+ n_1H_2O + n_2(1+e)(O_2 + 3,76N_2) = n_3CO_2 + n_4H_2O + n_5O_2$$
$$+ n_6N_2 + n_7CO + n_8CH_4 + n_9NO + n_{10}NO_2 + n_{11}SO_2 + n_{12}HCl$$
$$+ n_{13}KCl + n_{14}K_2SO_4 + n_{15}C + \cdots + \text{Energy}$$

In this reaction, the content of the fuel is expressed by second term. The fuel will not spontaneously react if excessive amount of moisture is present. The third term represents binary mixture of oxygen and nitrogen in the volume ratio of 21–79%. CO, hydrocarbons HC, oxides of nitrogen and sulfur as well as the inorganic species such as the alkali chlorides, sulfates, carbonates and silicates are the products of the reaction [16,69].

Biomass has high volatility and reactivity compared to conventional fuels. Therefore, it offers better combustion as a feedstock. The reactivities of carbonaceous materials are investigated using isothermal and non-isothermal thermo gravimetric techniques.

Ignition temperature and peak temperature are the most important characteristics of a burning profile. The ignition temperatures of the samples were determined from their burning profiles. The temperature at which the rate of weight loss due to combustion is maximum is called 'peak temperature'. The burning profile peak temperature is considered as a measure of the reactivity of the sample. The rate of weight loss at the burning profile peak temperature is called the 'maximum combustion rate'. All these characteristics are presented in Table 16 [14,65].

Table 19
Moisture, volatile and ash content of coal and biomass fuels.

Fuel	Moisture (% of fuel)	Ash (% of fuel)	Volatile matter (% of fuel)	Reference
Coal	4.8 ± 2.6	8.3 ± 1.5	2.4 ± 5.9	[71]
Oak wood	6.5 ± 0.8	0.5 ± 0.1	78.6 ± 3.8	
Wheat straw	7.3 ± 1	12.7 ± 3.6	64.0 ± 5.1	

Table 20
Typical properties of wood pyrolysis bio-oil and of heavy fuel oil [72].

Physical property	Bio-oil	Heavy fuel oil
Moisture content (wt%)	15–30	0.10
pH	2.50	–
Specific gravity	1.20	0.94
Elemental composition		
C	54–58	85
H	5.5–7.0	11
O	35–40	1.0
N	0–0.2	0.30
Ash	0–0.2	0.10
HHV (MJ/kg)	16–19	40
Viscosity (at 50 °C)	40–100	180
Solids (wt%)	0.2–1	1
Distillation residue (wt%)	Up to 50	1

6.5.3. Comparison of biomass and fossil fuels

Biomass generally has less carbon, more oxygen, higher hydrogen content and larger volatile component, more silica and potassium, less aluminum and sometimes calcium, titanium and iron and lower heating value compared to coal (Tables 17 and 18). Generally, biomass fuels work like low-rank coals [64,70].

High moisture, volatile and ash content are also notable properties for a of biomass fuel compared to coal. These properties are presented in Table 19.

Zhang et al. [72] shows the difference between bio-fuel and heavy fuel oil as shown in Table 20.

Compared to gaseous and liquid fossil fuels, the emissions of particulate matter from biomass are higher, leading to concerns about the availability of cost-effective techniques to reduce aerosol emissions in small scale biomass combustion plants [73].

The ignition process of biomass is similar to that for coal except there is more VM available for reaction in a biomass fuel. It is, therefore, more likely that homogeneous ignition will occur for biomass fuels [64].

6.6. Challenges of alternative fuels in industry

It is not an easy process to shift from fossil fuels to alternative fuels as many factors need to be considered. Suppliers and supply chains have not been fully developed on the scale necessary to supply volume of alternative fuels necessary to meet the global industrial sector needs. Coal was as a fuel for many years and supply chain and technologies are well established and matured. However, it is not clear at present how the alternative fuels supply chain will be or should be developed. Followings are the major challenges that need to be considered:

Table 18
Properties of coal and different biomass fuels [15].

Fuel name	Coal	Swedish wood	Straw	Palm kernels	Wood pellets	High-protein biomass
Inherent moisture (%)	4.38	9.53	8.31	9.3	5.43	1.95
Carbon content (%)	68.80	44.97	38.46	44.20	47.91	40.73
Volatile content (%)	32.50	81.32	72.00	71.63	79.16	79.12
Ash content (%)	12.12	1.82	14.24	4.24	2.55	27.88
Bulk density (kg/m^3)	1300	500	500	500	500	NA
Gross calorific value (kJ/kg)	27,444	17,211	15,354	18,719	18,711	174,410

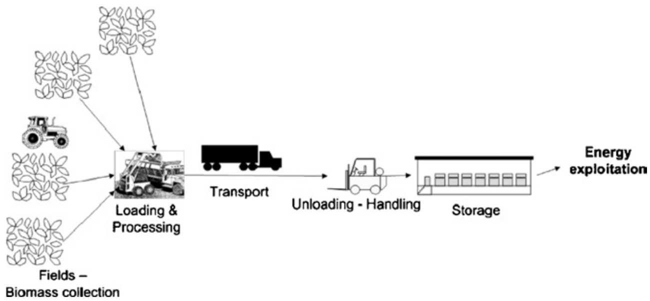

Fig. 29. Biomass supply chain design [74,75].

- *Supply chain*: One of the most important barriers in increased alternative fuel utilization in energy supply is the cost of the respective supply chain and the technology to convert alternative fuels into useful forms of energy. Fig. 29 shows biomass supply chain design [74,75].
- *Technical barrier*: In most cases there are only few local manufacturers or agents to supply equipment for the efficient conversion of various types of alternative fuels to energy. A network for the general maintenance as well as technical maintenance of this equipment is yet to be established.
- *Financial barrier*: High cost of production, lack of subsidies for energy production from renewable energy sources, and the energy pricing which excludes the external costs of energy use are the major barriers in this category. The front end costs for the newer technologies are comparatively higher and there are insufficient incentives for the use of these technologies. There is also a perceived financial risk which results in a lack of appropriate finances/credit mechanisms.
- *Policy and institutional barriers*: There is no national strategy or priority given to alternative sources of energy. Apart from this there are only few local expertise for renewable energy project feasibility study and design. Dissemination of information and awareness on renewable energy production technologies are also very insufficient. There is lack of coordination among various national agencies and designated agency responsible for undertaking renewable energy programs [76].

7. Conclusion

It was found that industrial sector consumes major share of total energy consumption of a country. Therefore, it is a potential sector that can be targeted for reducing energy consumption, using alternative sources of energy to mitigate environmental pollution.

Petroleum based fuels and coal found to be dominant fuels in this sector as technology is matured. These fuels are relatively cheaper compared to alternative or renewable fuels. However, these fuels are responsible for environmental pollution. Therefore, environmental friendly, clean, safe and economically viable fuels must be searched for. It may be noted that many countries are setting policies and priorities in favor of alternative sources of energy to encourage their usage.

Industries are using different sources of alternative energies to some extent. These are not largely used because of many challenges need to be faced with the usage of alternative fuels. Cost, energy transportation, supply chain, relevant expertise, technology maturity and appropriate policy are the major challenges that need to be addressed in order to use alternative sources of energy. Findings summarized in this report are expected to help in selecting an alternative fuel for industrial operation. The criteria shown in this paper may serve as a guideline in selecting an alternative fuel for an industry. It may also be suggested that research and development activities are needed to overcome the challenges reported in this paper.

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